Study of plasma wakefield acceleration mechanism for emittance dominated regimes via hybrid and pic simulations

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Abstract

Electron plasma wakefield acceleration (PWFA) mechanism is a promising non conventional acceleration scheme. Nonetheless further investigation is still needed to fully uncover the instability mechanisms so to mitigate them and make PWFA an effective tool. This work focuses in this direction, we discuss the necessity to use well matched driver bunches to further mitigate witness instabilities. Specifically we propose to inject driver bunches with larger emittance than the matched one (overcompressed bunch) so to let the system reach the matching condition by itself. This preliminary results lead us to the following consideration: while a limited number of cases can be studied with a particle-in-cell code, we understand the necessity for fast systematic analysis: we briefly introduce the hybrid code *Architect*.

Introduction

Plasma wakefield acceleration is a very promising particle accelerating mechanism, however, in order to bring such a technique to even more promising applications it is necessary to investigate the underlying plasma instabilities thus to mitigate them.

For this study we assume a standard two bunches configuration: the first bunch - the driver - is characterised with a charge of about 200 pC, a second bunch - witness - follows at about half a plasma wavelength ($1/2\ \lambda_p$, with a background number density $n_0 = 10^{16}\ \mathrm{cm}^{-3}$) with a much smaller charge: 10 pC. The driver induces the wakefield wave while the witness experiencing the field is accelerated.

We have observed that any driver betatron oscillations causes bubble oscillations, that eventually seed witness instabilities. Consequently, in order to further mitigate witness instabilities the driver bunch needs to be well matched to the background plasma. The matching condition [1] can be simply retrieved by the envelope formulation,

$$\sigma_{x,\mathrm{mtch}} = \sqrt[4]{\frac{d}{\gamma}}\sqrt{\frac{\varepsilon_x}{k_p}} \tag{1}$$

where $\sigma_{x,\mathrm{mtch}}$ is the transverse-rms matched dimension, γ is the relativistic gamma, ε_x is the emittance and k_p the plasma wavenumber. d is the bubble geometry parameter, $d = 2$ assumes a cylindrical bubble, $d = 3$ is used for spherical bubbles. The shape depends upon the bunch charge and dimensions. If we assume d=2, $\gamma = 200$ and $\varepsilon_x = 3$ mm-mrad, e.g. plausible values for the Sparc_Lab facility, we observe the driver being matched with a transverse size of 4.0 μm. We might consider a follower witness characterised by an emittance of $\varepsilon_x = 1$ mm-mrad -higher quality than the driver-; for such emittance value the matching transverse dimension is 2.5 μm. We can also make a physical consideration on the accelerator lattice: it is reasonable to assume that the linac lattice can be optimised for only one of the two bunches, and consequently while parameters can be accurately tailored for the witness, less control will be given to the driver.

The over-compressed driver-bunch

In the scenario described in the introduction: one driver plus a witness, we have introduced the necessity to control the driver matching conditions. We have also observed how controlling emittance and energy spread simultaneously for driver and witness is rather difficult nor whether impossibile. A possible solution may be achieved using an overcompressed driver bunch. The driver bunch is injected within the plasma channel with a transverse-rms

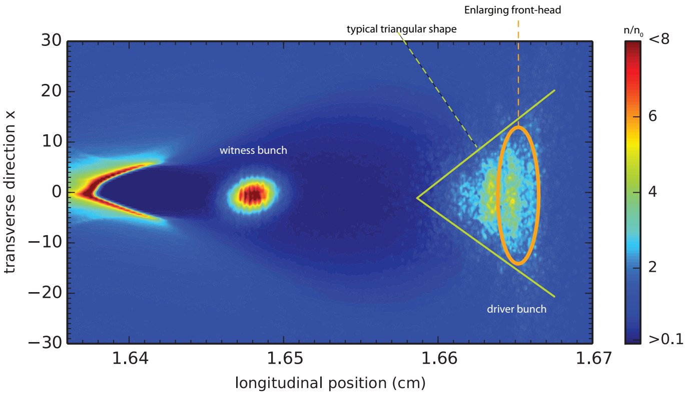

Figure 1: Two driver setup: a driver in front with a follower, reduced charge, witness. The driver characterised by a large emittance reach the characteristic cone profile.

Table 1: Equilibrium transverse size dimension, calculated by Eq.(2) and verified with the particle-in-cell code ALaDyn

emittance ε_x (mm-mrad)	$\sigma_{x,\mathrm{eps}}$ (μm)	σ_x-ALaDyn sim (μm)
1	2.0	2.4
2	4.1	3.9
3	6.3	6.0
4	8.4	8.8
5	10.4	10.0

dimension, σ_x, smaller than the matching one: $\sigma_x(t=0) < \sigma_{x,\mathrm{mtch}}$. This configuration is fairly easy to achieve by increasing the emittance. Physically: the emittance, that represents the internal bunch pressure, pushes to enlarge the bunch while the self generated electric field works to compress it. If the emittance is rather small (a few mm-mard) the bunch expansion is rather smooth and then tends to auto-stabilize around a matched configuration. The matched configuration is found by balancing the emittance pressure with the bubble electrostatic pressure, that reads:

$$\sigma_{x,\mathrm{eps}} = \sqrt{\frac{d^2(2\pi)^{\frac{3}{2}}\varepsilon_0}{2en_0^2 m_e}\frac{\sigma_z}{Q}} \tag{2}$$

with σ_z driver-rms size, Q total bunch charge, e electron charge, m_e electron mass and ε_0 the electric permeability in vacuum. Details of the calculation will be given elsewhere.

Eq.(2) theoretical calculations have been compared against the ALaDyn code[2, 3], results are summarised in table 1. ALaDyn is a particle-in-cell code recently adapted for electron plasma wakefield acceleration problems [4]. Table 1 shows that using $d = 2.5$, a bubble between a cylindrical shape and a spherical shape, the theoretical approximation well estimates the numerical calculations.

Systematic scans with an Hybrid approach: Architect

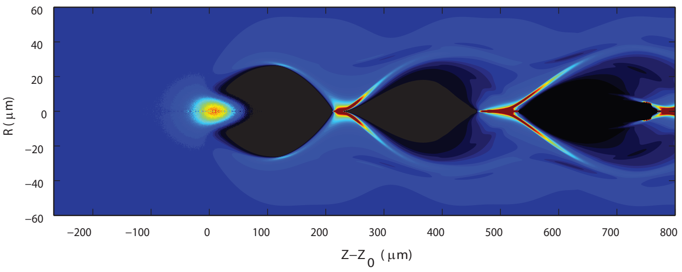

Figure 2: Electron number density of both driver bunch and background plasma in weakly nonlinear regime of PWFA, simulated with *Architect*

The study of the dynamics of both matched and expanding drivers, as the ones discussed in previous sections, need numerical systematic analysis; systematic scans are also necessary to fully uncover the sensitivity of the possible rising instabilities due to both plasma and bunch characterisation. Despite PIC codes are, today, heavily parallel on dedicated clusters-computers the amount of computational resources and the amount of computational operations restrict the use of such codes to proof of principles numerical investigations. While PIC codes do not seem a suitable numerical technique for heavy systematic scans, reduce models appears as the desired tool able to deliver a solution in a reduced time (minutes) without loss of accuracy. Architect, Fig.2, is a hybrid cylindrical symmetric code, it treats the bunches with a kinetic approximation while the background plasma is model as a fluid.

Since the background plasma, up to the quasi non linear regimes ($\widetilde{\mathbf{Q}} < 0.5$), exhibits an ensemble behaviour, it can be treated as a single large particle: a fluid cell. On the contrary, to catch the kinetic nature of the bunches a PIC-like approach is used. The critical, and somehow interesting part, is the interaction between the kinetic bunch scale, i.e. kinetic set of equations, and the fluid background electron plasma, i.e. the fluid equations. The interaction between the two scales is given by superposing the current induced independently by the bunches and the background plasma, inducing the total electromagnetic fields: $\mathbf{E}_{total}$ and $\mathbf{B}_{total}$. The overall evolution loop is depicted in Fig.3.Both electromagnetic and fluid quantities are evolved in a computational moving window shifted accordingly to the driver center of mass. Architect represents an effective and quick way to tackle the problem, nonetheless it appears a key tool for the experimental team since it can be used during experimental run to help the experimental team to take online strategic decisions.

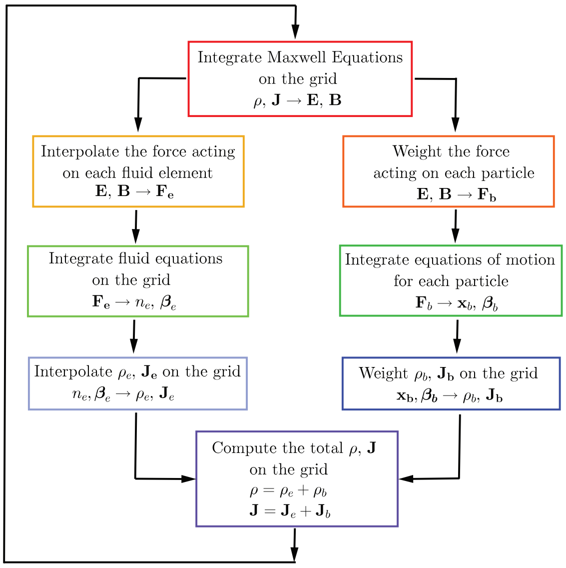

Figure 3: Architect loop.

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